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Seattle Fault location, earthquake recurrence and effects: Linking onshore and offshore records via shallow marine seismic surveys in the Duwamish Waterway and Elliott Bay, Seattle, Washington

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Abstract

Waterways offshore Seattle, Washington hold geologic records of active faulting, glaciations, volcanic activity, and intensive human modification. We collected 180 km of new, densely-spaced high-frequency seismic reflection lines that image the upper several meters of sediment in Elliot Bay (near the urban core of Seattle), the Duwamish Waterway (through the central Port of Seattle) and near Restoration Point (Bainbridge Island), spanning the width of the Seattle Fault Zone. The new seismic data capture features of submarine landslides, the Duwamish delta, a submarine feature that may be an old shoreline, and shallow deposits immediately offshore the Seattle waterfront. These data will contribute to a high-resolution map of submarine geomorphology and near-surface stratigraphy, from which we can interpret the features in the context of the area's depositional, tectonic, and anthropogenic history.

Report

Introduction

Seattle and surrounding urban areas are located in a tectonically complex environment that has been scoured and reworked by several Pleistocene glaciations (e.g., Mullineaux, 1970; Booth and Hallet, 1993) and extensively modified by humans (e.g., Bagley, 1929; Phelps, 1978). This geology complicates seismic hazard assessments for the region's three major earthquake producers: the Cascadia Subduction Zone megathrust, deep flexure of the subducting plate, and active crustal faults. Even though a prominent crustal fault crosses Seattle and neighboring cities, critical information about this fault zone remains unknown, including the position of the deformation front (e.g., Pratt et al., 2015; Mace and Keranen, 2012; Johnson et al., 1999), the specific geometry of the faults (e.g., Nelson et al., 2014; Kelsey et al., 2008); and the frequency of large earthquakes (e.g., Pratt et al., 2015; Haugerud et al., 2017).

Sediments in the waterways around Seattle contain information about fault-zone position, geometry and activity, but are also influenced by other processes. Repeated ice cover during Pleistocene glaciations deposited a drift plain composed of lenses of tills, sands, and silts (Mullineax, 1970), which was dissected by sub-glacial meltwater (Booth and Hallet, 1993). Resulting incisions hold Elliott Bay and the Duwamish River valley. Lahar sediment from Mount Rainier prograded the Duwamish delta through the valley to its current position, crossing the Seattle Fault Zone (Zehfuss, 2003). This fault produced a M ~7-7.5 earthquake 900-930 CE that raised the delta front ~6 m and triggered landslides (Bucknam et al., 1992; Atwater and Moore, 1992; Karlin and Abella, 1996; Atwater, 1999). Most recently, human activity dramatically altered the landscape. European settlers sluiced hillsides around the Seattle waterfront into Elliott Bay to accommodate urban development and dredged a straight channel through the Duwamish River delta to form the Duwamish Waterway (Bagley, 1929; Phelps, 1978).

The new seismic survey was motivated by the goal of studying the Seattle Fault Zone (SFZ) and its geologic context. The data collected cover the width of the SFZ where it encounters Seattle and provide new high-resolution images of near-shore sediment layers that were deposited or disrupted by the processes listed above, including faulting and related ground failure. The new survey samples the shallowest of these deposits with high depth resolution, imaging delta sediments atop the fault zone, clinoforms at the delta front, landslide scarps around bay margins, and features with glacial morphology on the bay floor.

During the award period, we conducted the new survey, processed the seismic data, and began interpretation of the resulting sub-bottom images. We will continue this interpretation effort to identify and map sub-bottom geologic features. We will integrate the new dataset with existing borehole data, other geophysical surveys, knowledge of the regional geology, anthropogenic modifications of the shoreline, and models of the Seattle fault.

Data collection and processing

We collected new ultra-high-resolution seismic (CHIRP) data offshore Seattle's urban waterfront (Elliott Bay and the urbanized remnants of the Duwamish River delta). Additional transects were acquired on the southeast shoreline of Bainbridge Island, directly west of Seattle in the Seattle Fault Zone. The data consist of approximately 180 km of seismic transects (more than twice our initial goal) within a 22 square km area (Fig. 1). The survey was conducted over five days in October 2019 aboard the R/V Weelander, a 15-ft vessel operated by the University of Washington School of Oceanography. We selected an ultra-high resolution, 2-16 kHz Edgetech 216s CHIRP system for its portability and the potential to resolve fine features, such as small fault splays or thin sedimentary layers. In ideal conditions, this class of seismic survey can achieve vertical resolution better than 10 cm. In exchange for this high resolution, the system employs high frequency seismic waves that attenuate more easily, resulting in shallower penetration than lower-frequency systems.

With our small boat and portable CHIRP system, we were able to survey where prior studies (with larger ships and larger equipment) could not, including close to shore and to the end of the dredged Duwamish Waterway, well beyond the southern margin of the Seattle Fault zone.

We tested the imaging capabilities of the 2-16 kHz CHIRP system for these near-shore environments in Puget Sound. Penetration of the seismic signal varied. Based on a 2017 sample line from deep water in Elliott Bay, we expected ~15 m in sub-seafloor penetration. Within bay-bottom sediments, imaging depth met or exceeded these expectations (Fig. 2). However, on shallower terraces and in the Duwamish Waterway, penetration was limited to only a few meters (Fig. 3). In prior surveys, poor imaging has been attributed to the presence of methanogenic gas. Alternatively, the locations with poor penetration may be regions of acoustically challenging lithology, such as non-uniform glacial deposits or irregular contacts, both expected in Puget Sound. Correlation of the stratigraphy imaged in these new seismic transects with observations from onshore geotechnical boreholes may help us distinguish between these possibilities.

Once back in the lab, the data was processed using a standard CHIRP processing flow that included heave correction and conversion to envelope. After processing, the data was collected in an interpretation project along with complementary datasets including seafloor bathymetry, terrestrial lidar and lower-frequency seismic data using IHS Kingdom Suite software.

Preliminary Results

The survey revealed a variety of features that will advance our understanding of the geologic and tectonic history of Elliott Bay. Initial review of images reveals candidate glacial ridges, clinoforms at the Duwamish delta front, and draped sediments that may derive from human activity. In the deep-water areas of Elliott Bay, the excellent sub-seafloor penetration should allow us to confidently map subsurface stratigraphy and correlate it to terrestrial stratigraphy derived from onshore geotechnical boreholes.

Here, we address our three initial objectives and discuss additional new findings.

One goal of the project was to look for evidence of surface-breaking back thrusts of the Seattle Fault Zone, which have been widely identified on land and in marine seismic surveys west of Seattle (Johnson et al., 1999; Nelson et al., 2003b; Brocher et al., 2004; Kelsey et al., 2008; Nelson et al., 2008; Liberty and Pratt, 2008; Nelson et al., 2014; Pratt et al., 2015). If some of these back thrusts or related structures continued eastward, they ought to cross Elliott Bay or the dredged Duwamish Waterway. None of the lines collected through the Duwamish Waterway revealed obvious evidence for fault offsets or warping. As described above, seismic penetration through the waterway was much shallower than anticipated (~1 m) so it is possible that shallow-breaking faults are present, but that we did not image them with the Edgetech 216s system. For future surveys, we would recommend trying a lower frequency CHIRP system such as the Edgetech 512.

A second objective was to image sediments at two submarine benches (in Elliott Bay and at Restoration Point) that may represent a marine-lowstand shoreline that was offset across the Seattle fault (Haugerud, 2017). We collected seismic profiles across both of these previously described benches, as well as several others noted in bathymetry, in order to map the benches and evaluate whether they are correlatable as a structural datum. CHIRP images also capture what appear to be bench-like reflectors buried below the seafloor surface (Fig. 4), without topographic expression. Prior work suggests that if these features are correlative, their vertical offset may limit the recurrence interval of large earthquakes to only one in the past 11,000 years (Haugerud, 2017).

A third objective was to image submarine landslides in Elliott Bay. Prior work suggests large and very large landslides in Puget Sound are controlled by activity on crustal faults (e.g. Smith, 2012), and have the potential to serve as paleo-tsunami sources, such as the 900-930 CE event that covered a tidal marsh at West Point, on the north margin of Elliott Bay (Atwater and Moore, 1992). Several candidates for such landslides are visible in Elliott Bay bathymetry and were described Gardner et al. (2001) and Smith, (2012). We collected longitudinal and transverse lines across several of these landslides with the goal of characterizing the source deposits for the slides, as well as the volume and extent of each slide. Analysis of lines across individual landslides is needed before we know whether or not the geologic record of landsliding remains complete; initial review of the data suggests that the deposits of at least some landslides are removed by other sediment transport processes in the bay.

In addition to our original objectives, we have identified additional scientific targets based on the new imaging in Elliott Bay:

Bathymetry in Elliott Bay shows a dramatic, linear, E-W trending channel crossing Elliott Bay from the Seattle Waterfront to Puget Sound. Since no modern drainage feeds the channel, it is unclear whether the channel is related to: the historical flow of the Duwamish River, drainages during sea-level lows, excavation by subglacial meltwater, or faulting. Based on low-resolution seismic imagery and an onshore geologic anomaly, Pratt et al., (2015) mapped the northernmost edge of the Seattle Fault Zone deformation front in the vicinity of the channel. Our new, ultra-high-resolution survey crosses the channel in several places, with generally excellent imagery. We anticipate that on-going examination of the new data may help differentiate among hypotheses for the origin of the channel.

Seismic lines across the Duwamish delta front image stacked reflectors that dip steeply toward the bay (Fig. 5). The delta established at its current position following rapid progradation through the Duwamish valley during eruptive periods of Mount Rainier. Mechanisms proposed for sedimentation include hyperpycnal flows of lahar-derived sediment (Zehfuss, 2003). We interpret the dipping reflectors to be clinoforms representative of delta-front sediments. Additional examination of the data may indicate whether these reflectors are lahar sands, and whether they are traceable into seismic images from the floor of the bay. Geotechnical borings sample tens of meters of lahar sands within the Duwamish river valley, but the volume of lahar sand that might have entered Elliott Bay is unknown.

In the past hundred years, people in Seattle reworked the morphology of the city by removing entire hillsides and sluicing them into Elliott Bay. Some apparently not-of-geologic-origin formations can be seen in both bathymetry and the new seismic lines. Adjacent to these, a classic “Holocene drape” layer of acoustically transparent material can also be imaged clearly throughout much of Elliott Bay that presumably represents that natural sedimentation in the bay approximately since glacial retreat. With the new data, we expect to be able to differentiate between anthropogenic and non-anthropogenic Holocene sedimentary deposits throughout this area. This should allow us to produce an estimate of the volume of anthropogenic sediment that remains in Elliott Bay relative to the ‘background’ natural sedimentation presumably associated primarily with riverine and estuary sediment sources such as the Duwamish River. This will be intrinsically interesting for assessing the anthropogenic impact on the bay, with associated implications for the ecological system, as well as for helping to constrain the distribution of anthropogenic deposits that might obscure fault-related features.

Ongoing work

We are continuing to collate lines and borehole information into a GIS in order to map and interpret shallow subsurface stratigraphy. Mapping will characterize general stratigraphy in Elliott Bay, capitalizing on shallow post-glacial strata and comparison with onshore observations. We are also in the process of synthesizing these diverse datasets, with the goals of better understanding how new observations relate to existing ideas on sediment depositional processes within Puget Sound, the geologic framework of our study area, and how these may be impacted by crustal faulting in the area.

Project Data

New digital data associated with the high-resolution seismic survey will be made publicly available via the National Archive of Marine Seismic Surveys (https://walrus.wr.usgs.gov/NAMSS/). We are in the process of communicating with colleagues at the USGS Coastal and Marine Science Center (Patrick Hart, hart@usgs.gov) to initiate the process of a data release. We expect a public data release will occur prior to the publication of the results from this study, which we anticipate in 2021.

Bibliography of work supported by this project to date

We shared our research plan and new data in a talk and a poster presentation at science meetings in 2019. We will present preliminary results in a digital poster for the December 2020 American Geophysical Union Meeting. We anticipate at least one peer-reviewed publication will result from this work in 2021.

Davis, E, J G Crider, E Roland, 2019. Paleoseismology across the shoreline in the Duwamish Waterway and Elliott Bay, Seattle. *Geological Society of America Cordilleran Section Meeting* (Portland, OR). https://gsa.confex.com/gsa/2019CD/webprogram/Paper329767.html

Davis, E J, J G Crider, E Roland, G Moore, 2019. New seismic reflection survey in Seattle basin and Seattle paleoearthquakes: evidence from an industrial river delta. Pacific Northwest Earthquake Science Workshop (Seattle, WA). https://sites.google.com/view/2019pnwearthquakescienceweek

Davis, E, E Roland, J G Crider, G Moore, 2020. High-resolution CHIRP survey offshore Seattle, Washington, American Geophysical Union Fall Meeting (online). *submitted.*

References cited in this report

Atwater, B.F., and Moore, A.L., 1992, A tsunami about 1000 years ago in Puget Sound, Washington: Science, v. 258, no. 5088, p. 1614-1617, doi:10.1126/science.258.5088.1614.

Atwater, B.F., 1999, Radiocarbon dating of a Seattle earthquake to A.D. 900–930 [abstract]: Seismological Research Letters, v. 70, no. 2, p. 232.

Bagley, C. B., (1929) *History of King County, Washington* (Vol. 1). S.N. Clarke Publishing Co, Seattle.

Booth, D.B. and Hallet, B., (1993) Channel networks carved by subglacial water: Observations and reconstruction in the eastern Puget Lowland o f Washington. Geological Society of America Bulletin, v. 105, p. 671-683.

Gardner, James V., van den Ameele, E. J., Dartnell, Peter, (2001), Multibeam Mapping of the Major Deltas of Southern Puget Sound, Washington: U.S. Geological Survey Open-File Report 01-266, *https://pubs.usgs.gov/of/2001/0266/*.

Haugerud (2017) Late last-glacial shorelines in northwest Washington State, Geological Society of America Abstracts with Programs. Vol. 49, No. 6, ISSN 0016-7592 doi: 10.1130/abs/2017AM-304915

Johnson, S. Y., S. V. Dadisman, J. R. Childs, and W. D. Stanley (1999), Active tectonics of the Seattle fault and central Puget Sound, Washington—Implications for earthquake hazards, GSA Bull., 111(7), 1042–1053

Karlin, R. E., M. Holmes, S. E. B. Abella, and R. Sylwester (2004), Holocene landslides and a 3500-year record of Pacific Northwest earthquakes from sediments in Lake Washington, Geol. Soc. Am. Bull., 116(1–2), 94–108, doi:10.1130/B25158.1.

Kelsey, H. M., B. L. Sherrod, A. R. Nelson, and T. M. Brocher (2008), Earthquakes generated from bedding planeparallel reverse faults above an active wedge thrust, Seattle fault zone, Geol. Soc. Am. Bull., 120(11–12), 1581–1597, doi:10.1130/B26282.1.

Mace, C. G., and K. M. Keranen (2012), Oblique fault systems crossing the Seattle Basin: Geophysical evidence for additional shallow fault systems in the central Puget Lowland, J. Geophys. Res. Solid Earth 1978–2012, 117(B3).

Mullineaux, D. R., (1970) Geology o f the Renton, Auburn, and Black Diamond quadrangles, King County, Washington. U.S. Geological Survey Professional Paper 672, 92 p.

Nelson, A. R., S. F. Personius, B. L. Sherrod, H. M. Kelsey, S. Y. Johnson, L.-A. Bradley, and R. E. Wells (2014), Diverse rupture modes for surface-deforming upper plate earthquakes in the southern Puget Lowland of Washington State, Geosphere, GES00967.1, doi:10.1130/GES00967.1.

Phelps, M. L., (1978) *Public works in Seattle, a narrative history of the Engineering Department 1875-1975.* Kingsport Press, Seattle.

Pratt, T. L., K. G. Troost, J. K. Odum, and W. J. Stephenson (2015), Kinematics of shallow backthrusts in the Seattle fault zone, Washington State, Geosphere, 11(6), 1948–1974.

Smith, S., (2012) Submarine paleoseismology in Lake Tahoe, CA/NV and Puget Sound, WA, University of Nevada, Reno, Ph.D. dissertation.

Zehfuss, P.H., Atwater, B.F., Vallance, J.W., Brenniman, H., and Brown, T.A., 2003, Holocene lahars and their by-products along the historical path of the White River between Mount Rainier and Seattle: Geological Society of America Field Guide, v. 4, p. 209-223, doi:10.1130/0-8137-0004-3.209.

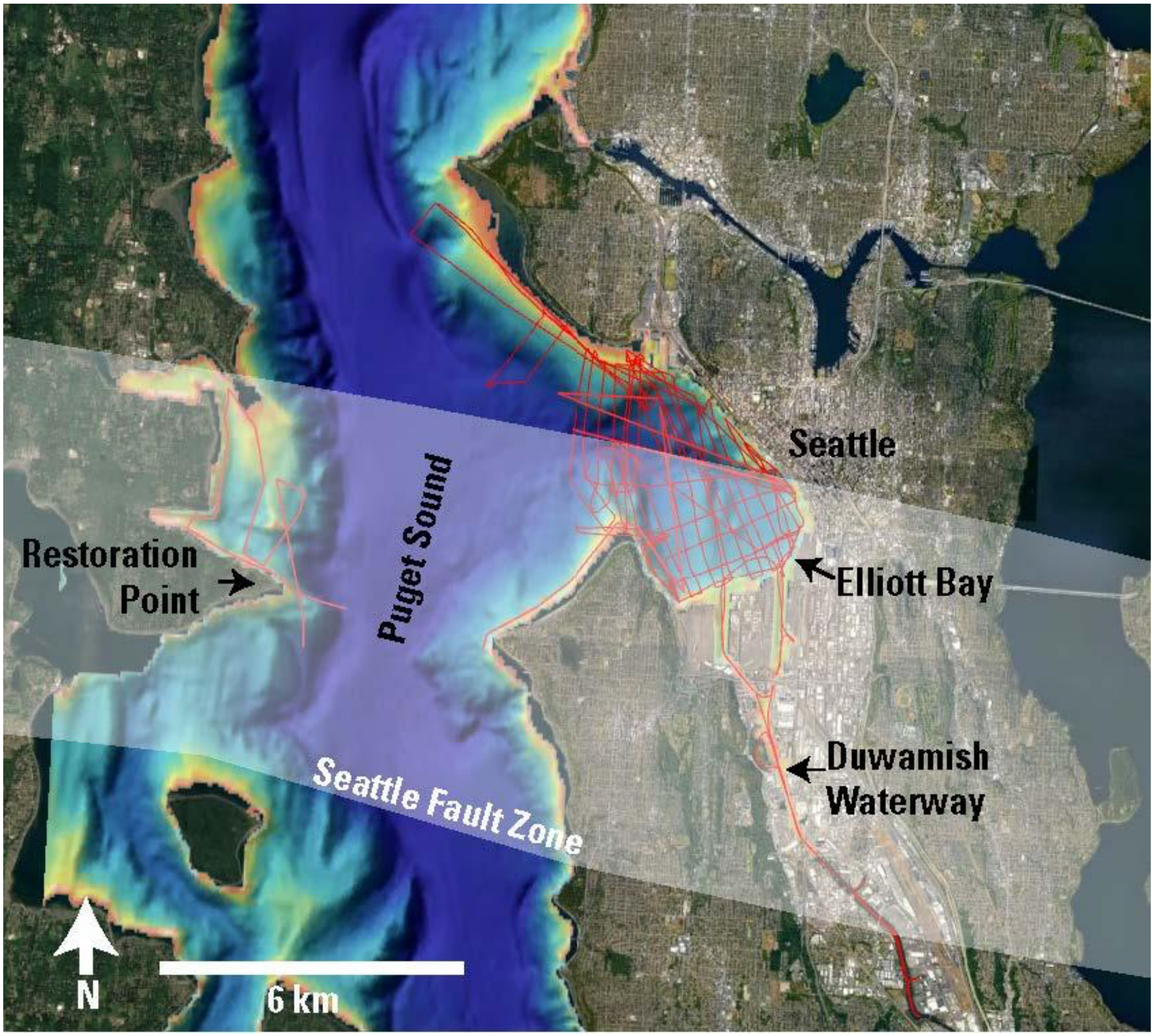

Figure 1. Regional map showing new CHIRP survey (red lines) collected October 2019, in context of Seattle-area landforms and bathymetry. The Seattle Fault Zone (white shadow) trends E-W across the area. Land imagery from Google Earth; multibeam bathymetry from recent NOAA surveys in color.

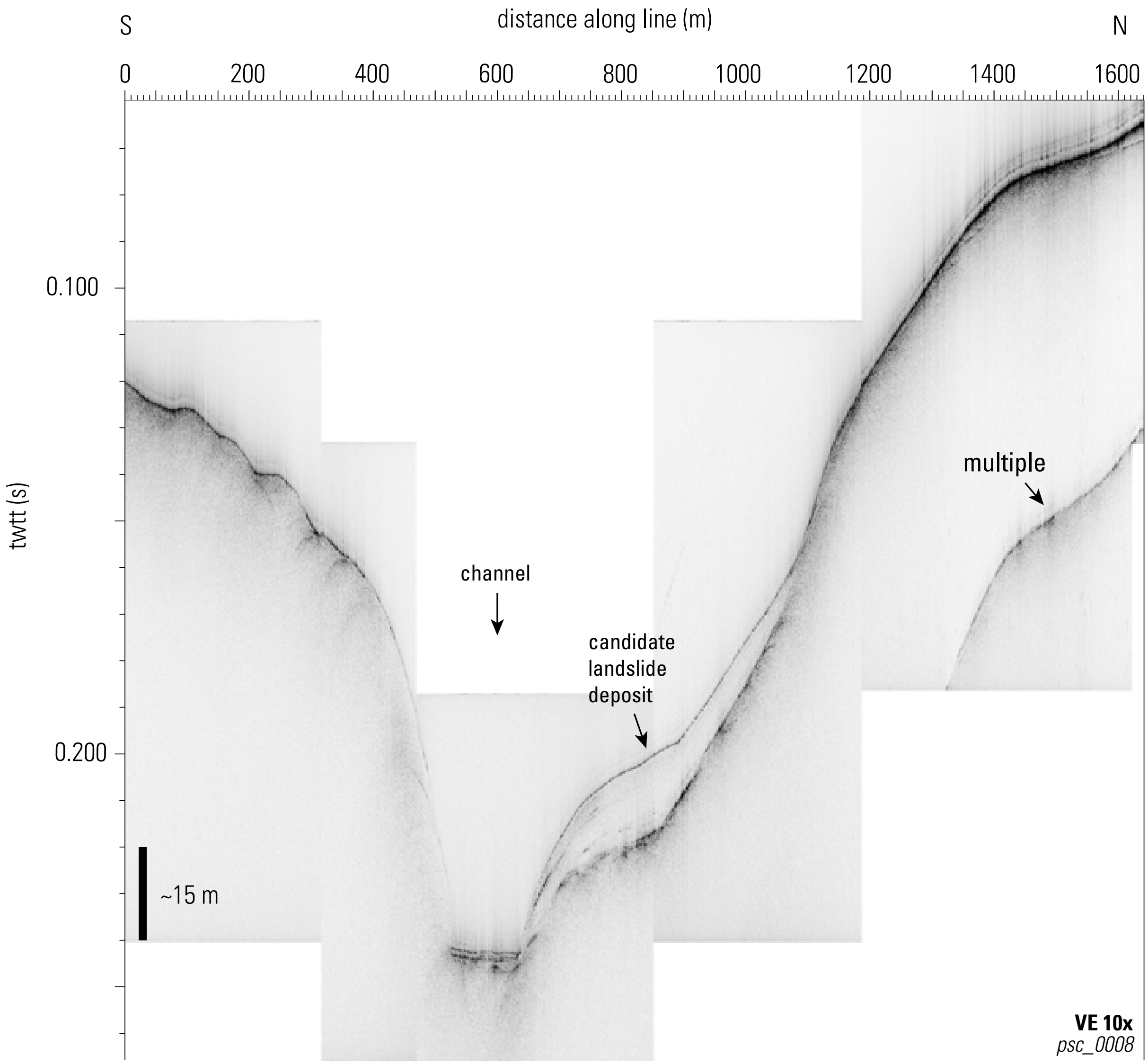

Figure 2. Sample CHIRP image crossing Elliott Channel and a potential submarine landslide deposit. In some areas, signal penetration meets or exceeds 15m. This image is drawn from unfiltered CHIRP envelope data, line psc_0008. Vertical exaggeration 10x.

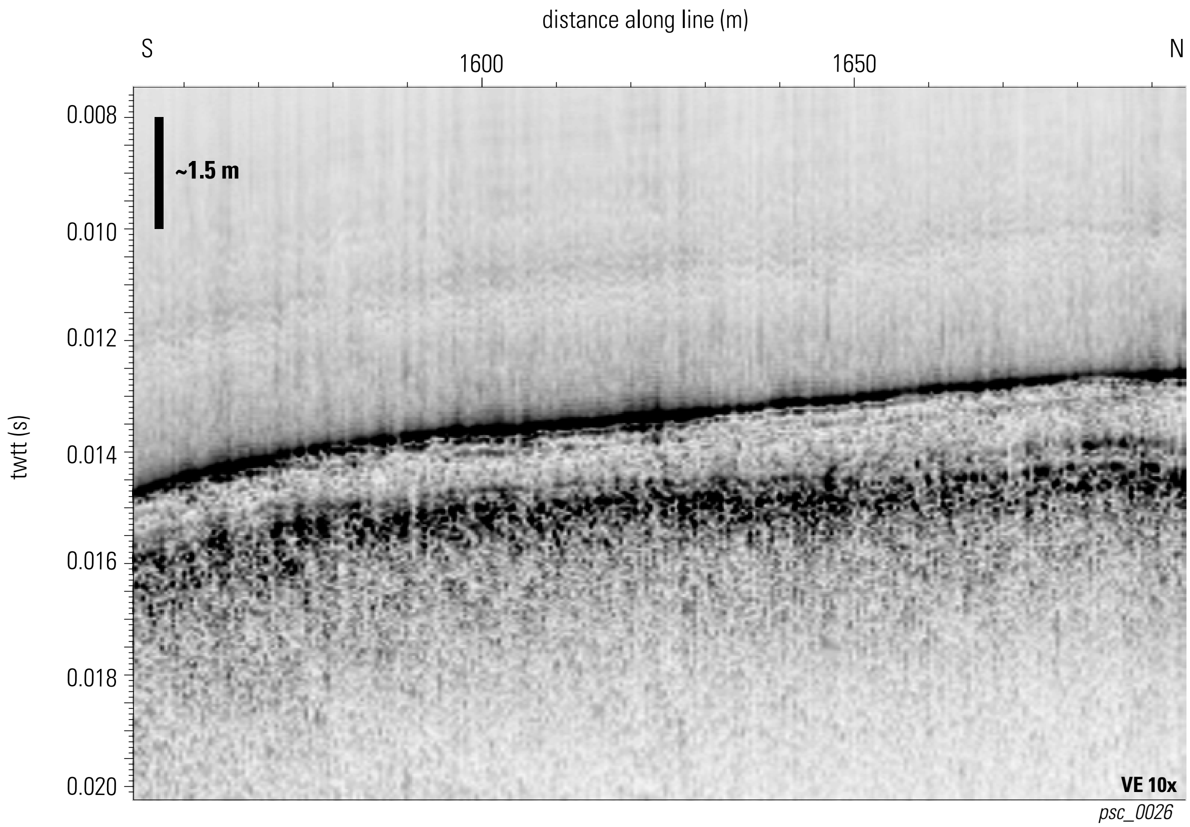

Figure 3. Sample CHIRP image from the Duwamish Waterway. Signal penetration is limited to under 2m. This image is drawn from unfiltered CHIRP envelope data, line psc_0026. Vertical exaggeration 10x.

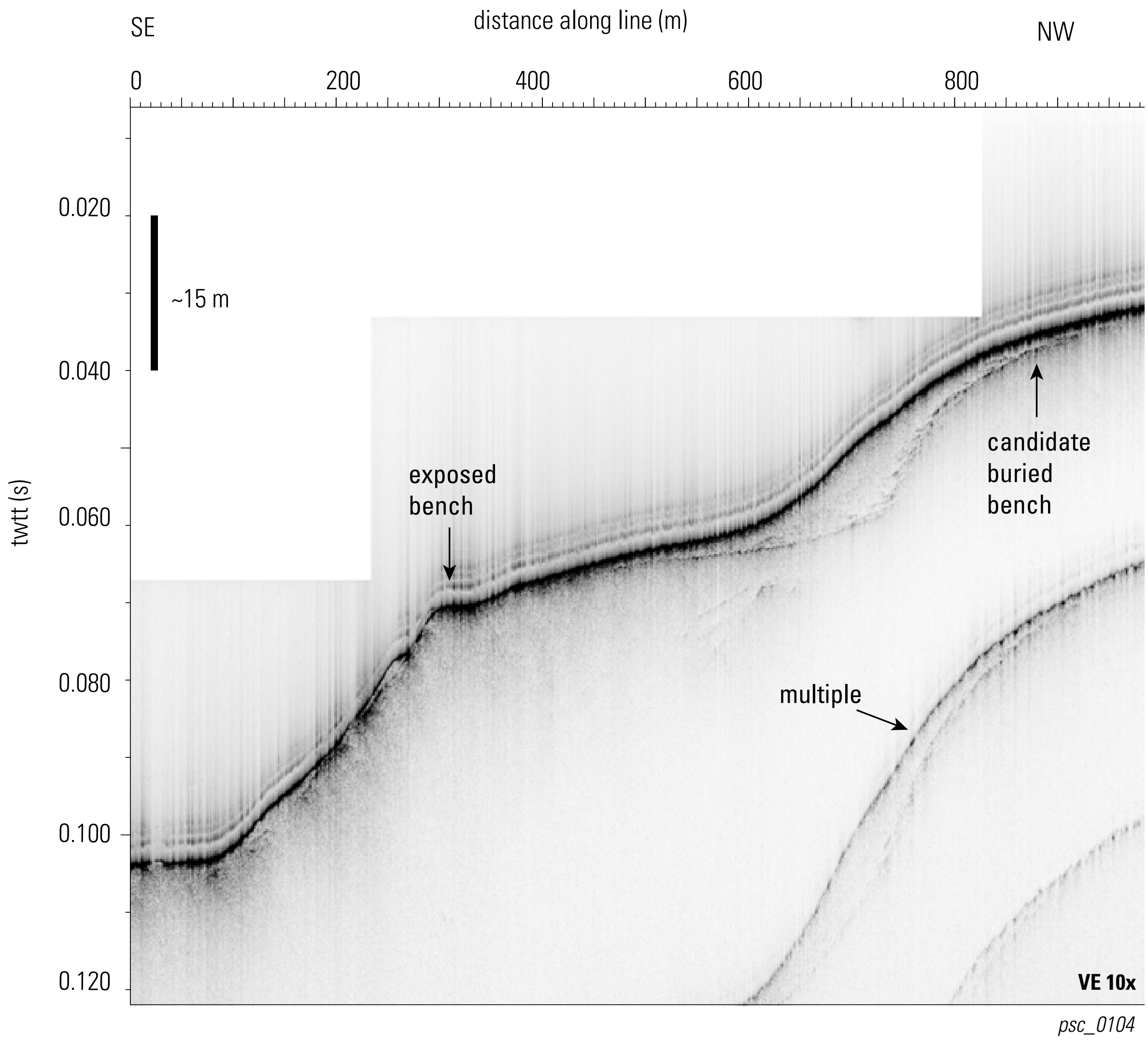

Figure 4. Sample CHIRP image offshore Restoration Point, showing a bench with geomorphic expression, and another similarly shaped reflector in the subsurface. This image is drawn from unfiltered CHIRP envelope data, line psc_0104, vertical exaggeration 10x.

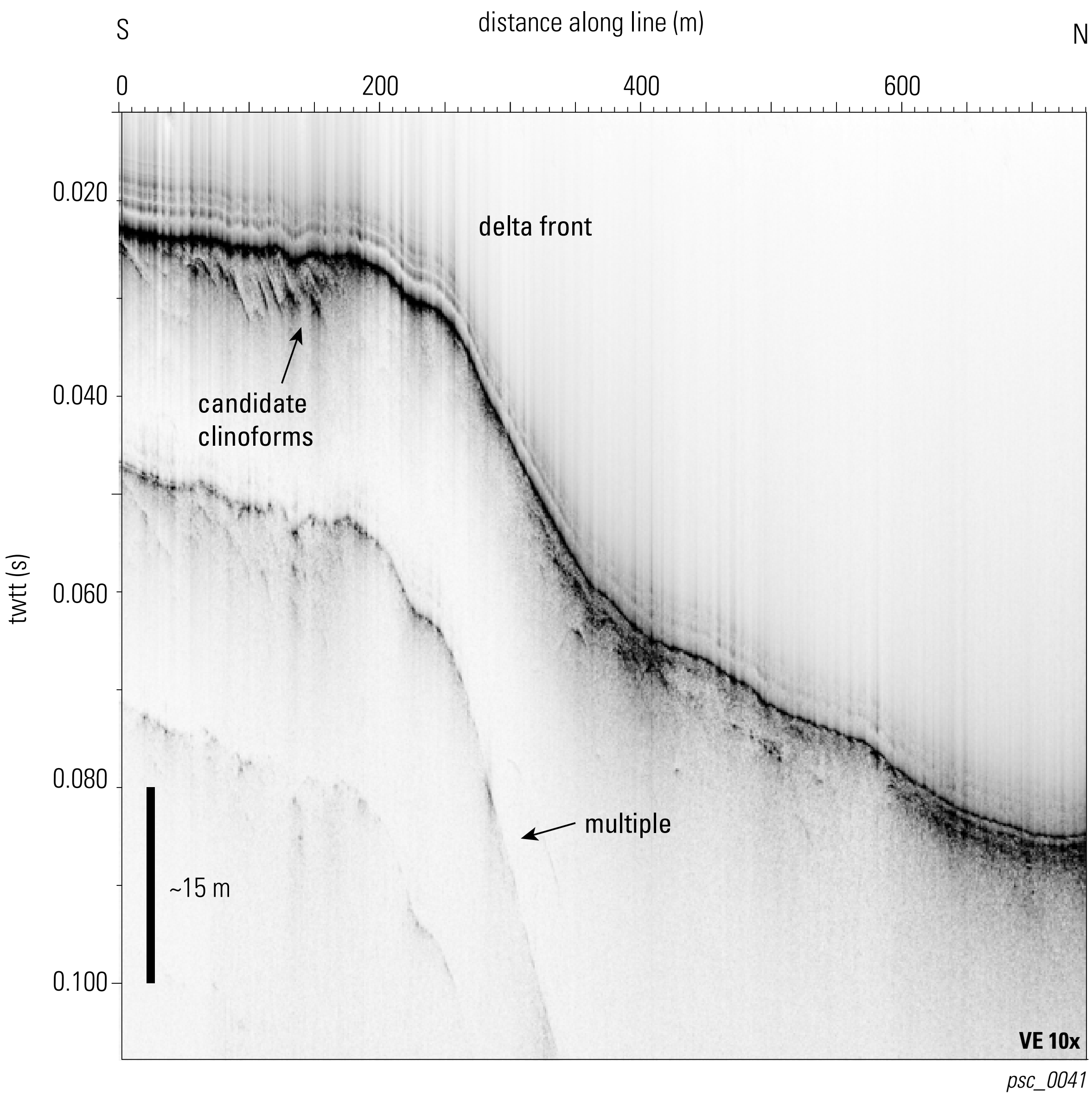

Figure 5. Sample CHIRP image at the Duwamish delta front, showing stacked reflectors that dip towards the mouth of the waterway. This image is drawn from unfiltered CHIRP envelope data, line psc_0041, vertical exaggeration 10x.